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The International Sailing Canoe: A Technical Review

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The unique features of the International Sailing Canoe have intrigued naval architects and sailors for years. This paper highlights the historical design development, describes current trends, and presents results from finite element analyses of three popular construction methods: cold-molded cedar, fiberglass, and carbon/epoxy. Comparisons are presented of the bending and torsional stiffness, pitch gyradius, and factors of safety. In general, the carbon/epoxy exhibited the best characteristics, followed by the cold-molded cedar and the fiberglass. The Tsai-Wu quadratic failure criterion developed for laminated plates was used in the factor-of-safety calculations. Factors of safety correlated closely to empirical development.

THE International Sailing Canoe (IC) has fascinated sailors and naval architects for years. Although outside mainstream sailing, its unique design and reputation for speed have maintained its esoteric reputation. The noted yacht designer L. Francis Herreshoff once wrote, "The sailing canoe is . . . one of the most interesting things that God has let man make" [1].[3] This paper highlights the IC's history, presents the current state of the art in IC technology, and compares structural analysis results based on current construction and analytical methods.

The paper is divided in four major sections. The first describes the IC and reviews some reasons why the IC interests naval architects. The second reviews historical IC development, emphasizing technical changes adopted in the quest for higher speeds. The third section presents current trends, and the fourth a technical evaluation of three typical construction methods. The different construction methods—cold-molded cedar, fiberglass sandwich construction, and carbon/epoxy sandwich construction—were evaluated using finite element analysis for factors of safety, radius of gyration and stiffness. These materials are also used in other sailboat classes, and the results illustrate the differences in current small boat construction.

Description

The IC (officially, the "International 10 Square Meter Decked Sailing Canoe") is a 17-ft monohull sloop raced single-handed. Figure 1 shows a modern IC sailing on San Francisco Bay. The principal dimensions of the IC are listed in Table 1, and a modern IC's profile view is shown in Fig. 2.

The IC class is considered a developmental one-design class, where certain aspects are controlled, such as total sail area, hull shape, and mast height. Other aspects, such as building materials, deck configuration, type of rig, and foil designs, are developmental [2]. The boats are raced without handicapping. Other well-known classes considered developmental one-designs are the International 14, the C-Class Catamaran, and the International America's Cup Class. For comparison, examples of stricter one-design classes include the Laser and J/24, and examples of handicap classes include the IMS and PHRF handicapping systems.

The general characteristics that interest the naval architect are readily apparent: the large length-to-beam ratio (5:1), the sliding seat, the very low displacement-to-length ratio, and the high sail area-to-displacement ratio. These make the IC a relatively fast boat. Speeds of 15 knots are common in stronger winds, corresponding to a speed-to-length ratio of 3.6. During the 1991 National Championships in San Francisco the lead canoes finished the 10-mile course in under 40 minutes, averaging over 15 knots. Another characteristic that interests the naval architect is the simplicity and limited restrictions of the class rules. This has allowed the IC to continue its development as experimentation is not restricted.

Approximately 300 IC's are actively sailed throughout the world, with active fleets in the U.S. (New England, Chesapeake, California), the U.K., Sweden, Canada, Australia, and Germany. The most recent World Championships drew over 60 competitors to San Francisco in 1993.

Historical development

The IC's developmental history is similar to many other racing sailboat classes in that it has been driven by the sailor's desire to increase boat speed and ease of handling within the class rules. As with most development classes, the current designs reflect the boundaries of the rules and not the limits of sailboat design. For example, the current seat extension limitation is 5 ft from the gunwale, and undoubtedly the boat would be faster in a breeze if the seat extension were increased to 5.5 ft. This point should be kept in mind when understanding IC development, as many of the improvements were a result of rule changes and many other potential improvements were either delayed or abandoned because of rule changes or limitations.

Early canoe racing (1865 to 1890)

The credit for inventing the sailing canoe belongs to British Army Captain John MacGregor. While recuperating from a railway accident in 1865 he designed a small boat for exploring the coasts of England and Europe. Designed mainly for use with a double-paddle, the boat was also rigged with a sail for downwind courses. The popularity of his book, *A Thousand Miles in a Rob Roy Canoe,* inspired others to build

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Fig. 1 The modern International Canoe

canoes and take up cruising, which led to the founding of The Canoe Club (later the Royal Canoe Club) in 1866 [3].

As the popularity of paddling and sailing canoes grew, more "canoe clubs" were founded. Many of these were located in areas that encouraged a particular aspect of canoeing; paddling (double-paddle), cruising, or sailing. In the latter category the New York Canoe Club (NYCC) was founded in 1871 to promote sailing races off Staten Island, and later City Island in New York Harbor. In 1880 the American Canoe Association (ACA) was founded to unite the efforts of canoe clubs across the country. In 1885 the NYCC offered a trophy, the New York Cup, for perpetual international competition ([3], p. 145). The New York Cup currently resides in the United Kingdom, having been won from the U.S. in 1993.

Table 1 Principal dimensions of International canoe

LOA/LWL	5.18 m (17 ft)
Beam (canoe hull)	1.02 m (3 ft 4 in.)
Seat extension from gunwale	1.52 m (5 ft)
Draft (board up)	0.11 m (4.3 in.)
Draft (board down)	1.12 m (3 ft 8 in.)
Weight (hull)	63 kg (138 lb)
Displacement	
(w/o crew)	88.5 kg (195 lb) (approx.)
(w/crew)	165.6 kg (365 lb) (approx.)
Sail area (actual)	10.6 m^2 (114 ft^2)
Disp/L ratio (w/crew)	33.2
Sa/disp ratio (w/crew)	35.7

Fig. 2 Sail plan

This trophy has the distinction of being the second oldest international yachting trophy after the America's Cup.

The canoes of that time were lightly carvel planked oak, mahogany, or cedar. The sailor would sit inside the craft and lean to windward to counter the sail forces. Figure 3 shows the sailplan of *Kestrel*, an example of an early cruising canoe. In 1886 Paul Butler introduced the sliding seat, which greatly increased the available righting moment and, hence, boat speed. Figure 4 shows an early sliding-seat canoe sailing in the Alameda Estuary of San Francisco Bay in the late 1880's.

British and American canoes diverge (1890 to 1933)

The next 40 years saw both a divergence of the British and American sailing canoe designs, and a decrease in the popularity of canoeing. In general, the American boats developed along the 16 × 30 line [16 ft (4.9 m) long and 30 in. (0.8 m) beam], and the British along a different development rule

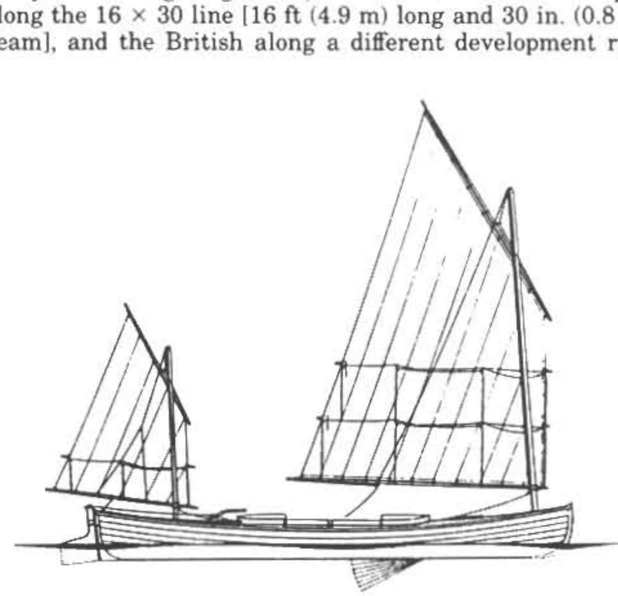

Fig. 3 Sail plan of *Kestrel*, circa 1890

Fig. 4 *Flying Scud*, an early sliding-seat canoe sailing on San Francisco Bay, circa 1890 (photo courtesy National Maritime Museum, San Francisco)

Fig. 5 *Mermaid*, 1914

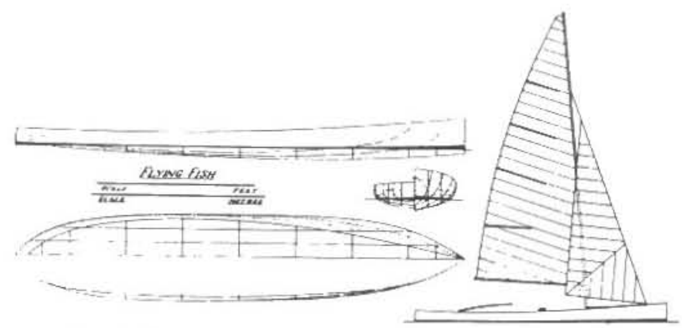

Fig. 6 *Flying Fish*, an early "International" canoe, circa 1936

encouraging longer boats with roughly 0.08 m (3 in.) greater beam and higher weight [about 18 kg (40 lb)]. The American boats had more sail area [10.3 m^2 (111 ft^2) versus 8.9 m^2 (96 ft^2)], but retained the unstayed cat-ketch rig [maximum height of 4.9 m (16 ft)], while the British adopted a sloop rig (no maximum height). Sliding seats on the American boats grew in length to 3.05 m (10 ft), the British banned their use, and full-length battens disappeared.

During this period very light wooden masts were developed. These 14-to-16-ft masts were made by spiral wrapping veneers which were held together by lacquer. The finished masts weighed as little as 6.4 kg (14 lb).

Figure 5 shows *Mermaid*, considered the ultimate development in the 16 × 30 class, as she with skipper Leo Friede won the New York Cup in 1914.

Various sailing canoes, including *Kestrel* (circa 1890), *Bee* (circa 1890), *Argonaut* (circa 1910), *Mermaid* (circa 1913, 1923) and an example of a "Rob Roy" Canoe (circa 1880), are well preserved at the Mystic Seaport Museum in Connecticut [4].

The "International" canoe is created (1933 to 1971)

In 1993 the British yacht designer Uffa Fox designed and built two canoes, *East Anglian* and *Valiant*, to comply with both the American and British rules, and challenged for the New York Cup. To get around the rule differences for rigs, a free-standing sloop rig using a solid fore-stay was developed. Although not as successful against the British canoes, Fox and Roger Quincy won the New York Cup, as well as the American National Championship [5].

The outcome of the English success was a joint proposal to create an international developmental rule for sailing canoes which combined the best features of each country's canoes. These included the sliding seat, greater sail area and lighter weight of the American boats, and the stayed sloop rig, longer length and greater beam of the British boats. Figure 6 shows *Flying Fish* (circa 1936), an early British boat designed to the International Rule [6]. Compared with the modern IC hull, *Flying Fish* is the same length, but is 3 in. narrower, and the aft chine is not as pronounced.

In both England and America canoe development progressed slowly. Different boats were faster in particular conditions, but no design was clearly superior in all conditions. Innovations continued, such as:

- easier steering controls,
- return of full-length battens in the 1950's,
- composite construction beginning in the 1960's,
- better hardware, and
- aft sliding seat carriages for downwind sailing.

The modern "International Canoe"

The growing popularity and ease of fiberglass construction allowed the class to adopt a one-design hull shape in 1971 to encourage "mass-production" of composite IC's. A design by Peter Nethercott was selected due to its good reputation in all conditions. Deck design, foils, rigs, and construction techniques were left developmental.

Although adopted for international competition, the one-design hull shape is not required for competition in the United States. In 1990 a single-chine canoe designed by Bill

Beaver to the U.S. National Rule won the U.S. Sailing Canoe National Championship.

Technological developments since the adoption of the one-design hull have focused on rigs, foil designs and hull construction. In 1984 Americans introduced carbon fiber masts at the World Championships and took the top three spots. Daggerboards with smaller sections and shorter chord lengths have proven faster than the older centerboards, experiments with rotating rigs continue, and carbon has found its way into the hulls and other structure.

State of the art in sailing canoe design

Modern IC technology reflects current trends in yacht design. This section presents the design and construction trends and the last section presents structural analyses of current construction methods.

Hull construction

Rule 6(g) of the IC Rules governs hull construction, and simply states, "There are no restrictions on the material or method of construction of the hull" ([2], p. 15). Some limitations however do exist: a minimum weight of 63 kg (138 lb) with a limit of 5 kg (11 lb) of corrector weights for the stripped hull, and enough buoyancy to support 75 kg (165 lb) with the hull flooded. Two practical considerations not included in the rules are also considered, toughness and cost. Currently canoes are built with one of a combination of cold-molded wood construction, fiberglass (with or without a core), or advanced composite construction.

The following three subsections briefly describe current practices for each method. Because IC's are rarely "mass produced," few canoes are identical. This characteristic limits the following descriptions to general practices with a few examples. Some of the economic considerations of each method are compared and later the different methods are compared analytically.

Wooden hull construction—During the first 100 years of sailing canoes, hulls were made of wood. In order to minimize drag, carvel and strip planking were common, although some boats were lapstrake planked. After the Second World War canoes began to be molded. A number were hot-molded using Resorcinol glue, but with the increased availability of room-temperature-cure epoxy resins, cold-molding became more common. Today some cold-molded boats are produced in Australia, Britain, Canada, and Japan, particularly in areas where molds for composite construction are not available.

Cold-molding involves the laying of thin veneers of a lightweight wood over a temporary male mold. The veneers are typically held together by epoxy, although other glues may be used. In the United States the technique is best known as the WEST system developed by the Gougeon Brothers [7]. The finished product is a strong, light, monocoque structure exhibiting high flexural stiffness and fatigue properties. In classes where construction rules prohibit "advanced composites" (typically carbon or Kevlar), cold-molding offers a competitive alternative to fiberglass construction.

The primary options in cold-molding are the number and thickness of each veneer, the species of wood, and the veneer orientation relative to the boat's centerline. In IC construction the number of veneer plies ranges from 2 to 5, and the thickness of each veneer from 1.6 to 3.2 mm (1/16 to 1/8 in.). The resulting skin thickness is typically between 6.4 and 9.6 mm (1/4 to 3/8 inch). In North America, Western Red or Port Orford cedar is commonly used, although mahogany may be used as the outer ply for additional toughness, and a layer of 60 to 200 g/cm^2 (1.75 to 6 oz/yd^2) fiberglass cloth may be added to the outside for abrasion resistance.

Stacking sequences range from [90°/0°] (to the centerline) for a two-ply laminate, to a more complicated laminate including off-axis plies of 45° or 30°. The advantages of using more plies are greater control of properties, and a generally higher fatigue life due to the reduction of shear loading on the glue. The disadvantages are a higher weight for a given thickness due to the additional glue, and more labor. The preference and actual superiority of one over the other is a function of the amount of effort and quality the builder can tolerate. Generally, about 40 man-hours are required to lay a single layer of veneer on a canoe hull (personal communication with Fran DeFaymoreau, Feb. 1992).

Fiberglass hull construction—The desire to reduce construction times (and costs for non-owner-built boats) inspired canoe sailors to try fiberglass construction. In the United States, Lou Whitman, who dominated American IC development and sailing from the 1940's to the 1970's, built the first fiberglass boats in the late 1960's. During the 1970's and 1980's, Steve Clark, Ted Van Dusen, and Erich Chase further developed the fiberglass IC. These boats were built using materials and methods common in other small craft construction, and many are still competitively raced.

Typical fiberglass construction involves the saturation of a dry (E-glass) fiberglass cloth with a polyester resin, the plies being placed in a female mold. In areas where greater flexural stiffness and strength are required, a core is used between the plies. In general, fiberglass laminates are cured at room temperature and pressure. The options in fiberglass construction are similar to cold-molded construction: ply thickness, cloth format and weight, and ply orientation [8]. A typical IC fiberglass hull lay-up takes about 6 man-hours.

Fiberglass American sailing canoes typically were built with between 850 to 1020 g/cm^2 (25 to 30 oz/yd^2) (dry) outer skin laminates and 270 to 410 g/cm^2 (8 to 12 oz/yd^2) (dry) inner skin laminates, with core thickness ranging from 3.2 to 9.6 mm (1/8 to 3/8 in.). The cloth warp direction was generally laid perpendicular to the centerline for greatest economy. Most canoes were "composite" construction, with fiberglass hulls and plywood decks. The service-life problems of these boats included insufficient strength in the plywood decks and a "softening" with age due to the low fatigue resistance of polyester resin combined with a light E-glass laminate [9]. Two factors led to the use of advanced composite construction in the IC: the desire to build boats with longer competitive life spans and lighter "ends," and the goal to avoid many of the service life problems of the wood and fiberglass boats.

Advanced composite construction—The term "advanced composite" construction in the marine industry generally refers to the use of higher-modulus reinforcement fibers and higher performance resin systems than the typical polyester/E-glass combination used in "fiberglass" construction. In some cases the term also includes unidirectional E-glass fabrics, and some "advanced" construction techniques such as vacuum-bagging.

IC builders began using these advanced materials and techniques in the early 1980's on components offering the greatest performance increase. These included braided carbon fiber masts developed by Ted Van Dusen and vacuum-bagged carbon fiber daggerboards by Steve Clark. The materials were generally room-temperature cured epoxies combined with a T-300 grade carbon. Using carbon reduced the mast weight by 30%.

Carbon did not find its way into IC hulls until the late 1980's. American canoe builders first began by orienting unidirectional plies to match the load directions, and tapering cores in the lower stress areas near the bow and stern. During the mid-1980's vacuum-bagging, to increase the ply com-

paction and reduce the resin content, and later post-curing to increase the resin properties, became routine.

Economic comparison of hull materials—Table 2 compares estimated costs to build an IC using the three methods described above. As with any cost estimate, the assumptions drive the bottom line, but valid conclusions can be made by adjusting the assumptions to fit a particular case. In this case the actual material costs and labor hours were considered, with the assumption the builder had the necessary molds and tools available. The wood boat was assumed to consist of a three-layer hull, and the composite boats were five plies plus a core; decks were slightly lighter. In each case, costs for hardware, sails, mast and rigging were identical, and represent current designs.

The comparison shows that based on the material costs alone, the fiberglass and wood boats are approximately equal, but an all-carbon boat is approximately 65% higher. With an arbitrary labor rate of $10/hr included, the fiberglass boat is now 22% less than the wood boat, and the carbon boat is 20% higher than the wood boat. For a three-layer wood boat, the break-even point with a carbon boat would occur when the labor rate was $25.50/hr, and a four-layer wood boat would break even at about $15.50/hr. Figure 7 compares the effects of labor rates on the total cost of a three-layer wood, a four-layer wood, a fiberglass, and an all-carbon IC.

A boat combining carbon and glass in the same laminate would fall between the fiberglass and all-carbon lines, and depending on the amount of carbon used and the labor rate, it may be more economical than a wood boat.

Table 2 Cost estimates for different construction techniques

Material:	Wood	Fiber-glass 5-ply	Carbon/Epoxy 5-ply
Laminate:	3-layer	w/core	w/core
Labor:			
hull	120	30	60
deck	40	30	40
hardware	20	20	20
daggerboard	15	10	10
rudder	20	20	20
rigging	15	15	15
total labor hours	230	125	165
labor rate per hour	$10.00	$10.00	$10.00
Materials (hull, deck, seat, foils):			
wood (ft^2)	485	115	115
resin (gal)	4.3	5.3	5.1
cloth (ft^2)	71.5	825	825
wood ($/ft^2)	$0.90	$1.20	$1.20
resin ($/gal)	$44.00	$32.50	$44.00
cloth ($/ft^2)	$0.21	$0.36	$2.35
wood cost	$436.50	$138.00	$138.00
resin cost	$189.20	$172.25	$224.40
cloth cost	$15.32	$294.64	$1938.75
hardware cost	$475.00	$475.00	$475.00
sail cost	$650.00	$650.00	$650.00
mast and rigging cost	$875.00	$875.00	$875.00
Total material cost:	$2641.02	$2604.89	$4301.15
Total labor cost:	$2300.00	$1250.00	$1650.00
Total cost:	$4941.02	$3854.89	$5951.15

NOTES:

1. Man-hour and material estimates based on discussions with current canoe builders.

2. Material cost estimates from quotes obtained between Jan. 20 and Feb. 25, 1992, and do not include taxes.

3. Labor rate for comparison purposes only.

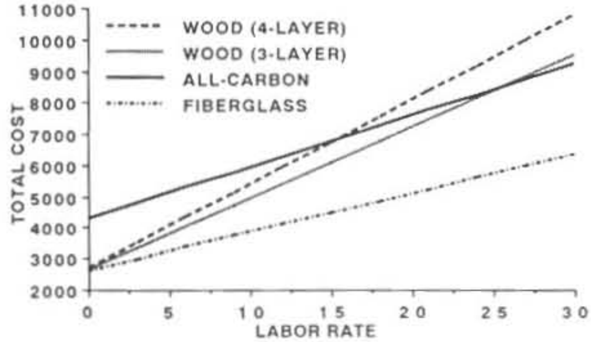

Fig. 7 Labor rate versus total cost of an International Canoe

Rig design and construction

Adopting the one-design hull shape forced canoe designers to look elsewhere for performance improvements. One area receiving attention was the rig. Improvements were sought in aerodynamics and rig weight reduction. The reduced rig weight would improve boat speed in waves, and improve boat handling characteristics. This subsection highlights the current state of the art in rig development.

Rig materials—The IC rules do not restrict materials used in mast or boom construction, and no minimum weight is required ([2], p. 16). Masts weigh 10 to 20 lb when rigged. Current IC masts are made of wood (strip-planked or traditional hollow construction), aluminum, or carbon (braided or hand lay-up). Each has its advantages, and none seems to dominate the competition. Table 3 lists many of the trade-offs in material selection. Note that carbon masts are typically less expensive than aluminum masts in the U.S. because carbon masts are manufactured domestically and the preferred aluminum masts are made in the U.K.

Rig design—The IC rules limit rig design in the following ways ([2], pp. 16, 17)]:

(*a*) The thickness of a rotating mast shall not be less than ⅔ of the chord at the same position.

(*b*) A maximum mast height of approximately 6.25 m (20 ft 6 in.) above the water.

(*c*) The total measured sail area (all sails) is 10.6 m^2 (114 ft^2).

(*d*) The mainsail must be able to be lowered while on the water.

Current rigs generally fall into two categories, fixed or rotating, with fixed rigs preferred by about 95% of canoe sailors. The main advantages of the single-spreader fixed rigs are lower weight, easier tuning in different conditions, and a mature sail design to match the mast's bending characteristics. Mast sections are typically round with diameters ranging from 50 to 65 mm. Fixed rigs took the top three spots at the last World and National Championships.

Rotating rigs are still considered in the experimental stage, with wide variation in design concepts. Three rigs showing the most promise were the single-luff aluminum mast rig developed by Chris Converse in the early 1980's, the double-luff spruce-carbon mast developed by Paul Miller in the late 1980's, and the single-luff carbon rig developed by Erich Chase in 1990. All three rigs won races in light to moderate conditions, but did not perform well in strong winds. The best performance of the Converse rig was second place at the 1984 World Championships. The Miller rig won the 1989 North American Championships, and the Chase rig won one race at the 1990 World Championships.

The main disadvantages of the rotating Converse rig was the higher weight than the fixed rigs, which increased pitch-

Table 3 Rig material comparisons

Material/ Characteristic	Wood	Aluminum	Carbon
Pros	Easily customized Inexpensive Amateur construction	Wide selection Consistent properties	Relatively inexpensive Light
Cons	Lower properties Inconsistent properties	Heavy	Limited selection
Cost (unrigged)	\$50–\$200 (home built)	\$600–\$950	\$500–\$650

ing in waves, and the lack of control over mast bend, which resulted in a loss of rig tension and pointing ability in strong winds. The Chase rig solved the first problem by using carbon/epoxy in place of aluminum. Mast control remained a problem, however.

The Miller rig was designed with a larger cross-section for increased stiffness to maintain rig tension for the same weight as the aluminum masts. To offset the increase in mast-diameter-induced drag, a double-luff mainsail was used. This rig type was originally designed and patented by L. Francis Herreshoff for use on the R-boat *Live Yankee* in the late 1920's, but the rule makers outlawed its use before it could be tested ([1], p. 21). To maintain the same mainsail weight as the single-luff sails, a lightweight Mylar-film sail was used. This rig showed promise, but heavy weather performance was not equal to the fixed rigs due to difficulties controlling mast bend. Both the Chase and Miller rigs also suffered from a lack of sail development.

Structural analysis of modern canoe construction

The three construction methods described earlier were compared using finite element analysis (FEA). The purpose was to determine what impact the added technology would have on the performance of the IC, and where modifications could be made to reduce weight in the ends of the boat.

Finite element analysis is a mathematical method of determining deflections and stresses in a structure. The structure is broken up into smaller "elements," each of which is given stiffness and strength parameters based on shape, type of element, and material. A mathematical representation of the structure is then constructed in matrix form based on these stiffness parameters. This stiffness matrix is then used to solve for the resultant structure displacements by using the applied force vector and basic matrix algebra. Stresses in the elements are found through back substitution using the stiffness matrix and solved displacement vector. Finite element analysis has been widely used in the aerospace and other industries since the 1950's, and its increase in use has paralleled that of the computer due to the computationally intensive nature of FEA [10].

These analyses were performed using COSMOS/M, a general-purpose finite element code run on a personal computer. Due to the simple design, a global model was built using composite shell, beam, truss, mass, and isotropic shell elements [11]. Every major structural component on a typical IC was modeled, including the sails, rig, foils, and sliding seat. The model was loaded using uniform pressures based on an upwind sailing condition applied to the sails, hull, and daggerboard, and was constrained at the aft end of the boat. These boundary conditions do not produce actual vertical deflections due to the imbalance of localized vertical forces, although relative vertical deflections occurring forward of the constraints are accurate.

The completed model size was 2602 nodes, 2942 elements, 15 600 degrees of freedom, and took approximately two hours to complete the linear analysis. Each analysis required approximately 60 MB of hard disk space, and each model was evaluated in four areas: bending stiffness, midsection torsion, pitch gyradius, and factors of safety. The method of approach used in these analyses was based on previous work by the authors for Team Dennis Conner's 1992 America's Cup defense effort.

Model descriptions

A standardized "typical" IC was used for all three models, so that the only differences would be in the structural materials. Between models, different laminates were used in the foredeck, main deck, hull, chine area, and bulkheads. These laminates are given in Table 4 for each model. The materials used in each model were typical values for those used in IC construction, and the material properties used in the analyses are listed in Table 5. In general, a 0-deg ply is considered to be fore/aft, and the plies are listed from inside to outside. For bulkhead laminates, 0 deg is athwartship, and the stacking sequence is given from aft to forward. A four-layer wooden boat was chosen for modeling due to the greater efficiency of the four-layer stacking sequence.

The mast, boom, and forestay were modeled as beam elements; the mast properties were based on a carbon fiber mast. The forestay was preloaded with a 250 lb force. The

Table 4 Laminates used in IC models

Laminate	Wood Model	Fiberglass Model	Carbon/Epoxy Model
Hull fwd of mast	[−45/45/90/0]	[0:2/0.125 in. core/0:3]	[0/45/0.125 in. core/0/45/0]
Hull aft of mast	[−45/45/90/0]	[0:2/0.25 in. core/0:3]	[0/45/0.25 in. core/0/45/0]
Chine	[−45/45/90/0]	[0:5]	[0/45/0/45/0]
Foredeck	[0/90]	[0/0.0625 in. core/0]	[0/0.0625 in. core/0]
Main deck	[0/90/90/0]	[0/45/0.25 in. core/45/0]	[0/45/0.25 in. core/45/0]
Bulkheads	[0/90/90/0]	[0/90/0.5 in. core/90/0]	[0/90/0.5 in. core/90/0]
Kingplank	[0/90/90/0]	[0/90/0.25 in. core/90/0]	[0/90/0.25 in. core/90/0]

Table 5 Material properties used in analysis

Material:	Cedar/Epoxy	E-glass Cloth	Carbon Cloth	Uni E-glass	Uni Carbon	Core
Mfg. desig.	...	181	282	6 oz.	5 oz.	9 lb/ft^3
Oz/yd^2 (dry)	18.0	8.9	4.7	6.0	5.0	26.2
Property:						
E_x (msi)	1.6	3.0	9.2	5.6	17	0.07
E_y (msi)	0.075	3.0	9.2	0.5	0.5	0.07
G_{xy} (msi)	0.075	0.5	0.9	0.5	0.9	0.03
Nu_{xy}	0.3	0.04	0.06	0.27	0.3	0.3
X_t (ksi)	8	50	85	135	200	0.15
X_c (ksi)	4	28	77	88	120	0.25
Y_t (ksi)	0.25	47	83	4.5	8	0.15
Y_c (ksi)	0.4	28	74	17	14	0.25
XY_t (ksi)	1	1.8	19	8	11.1	1
X_t (lb/in.)	500	400	765	743	1200	38
X_c (lb/in.)	250	224	693	484	720	63
Y_t (lb/in.)	16	376	747	25	48	38
Y_c (lb/in.)	25	224	666	94	84	63
H_o (in.)	0.0625	0.008	0.009	0.0055	0.006	0.25
Spec. density	0.39	2.6	1.75	2.6	1.75	0.14
Fiber dens. (pci)	0.014	0.094	0.063	0.094	0.063	0.005
Fiber vol.	99%	57%	40%	56%	64%	100%
Resin weight	5%	27%	53%	28%	30%	0%
Ply wt (oz/ft^2)	2.10	1.36	1.11	0.93	0.79	2.91
No. of plies in hull	4.00	5.00	5.00	...	...	1.00
Skin weight (lb)	34.1	27.6	22.5	...	...	11.8
Hull weight (lb)	Wood	Fiberglass	Carbon	...	...	...
	34.1	39.5	34.4	...	...	...

NOTE: These material properties are for analytical purposes only and should not be used for design.

shrouds were modeled using truss elements to represent the end conditions of wire rigging used on an IC. Only the windward shroud was modeled, as the leeward shroud is slack during upwind sailing. In all three models, a wooden seat and seat carriage were modeled, with a 79 kg (175 lb) mass (representing the sailor) placed on the outboard end. Figure 8 shows a typical undeformed and deformed model, as produced in these analyses.

Bending stiffness

Bending stiffness was evaluated by taking the vertical deflections at the bow, shroud attachment, and mast step and finding a total deflection at the mast step by using the formula

$$\text{Total } \delta = (\delta \text{ shroud} + (\delta \text{ bow} - \delta \text{ shroud}) \times 12.94/82.66) - \delta \text{ mast step}$$

The model with the lowest overall deflection had the highest bending stiffness. Bending stiffness is important as it affects the rig deflections, sail shape, and hull shape; stiffer is considered better. The overall deflections for each of the three baseline models are presented in Table 6, and a contour plot of resultant deflections is shown in Fig. 9.

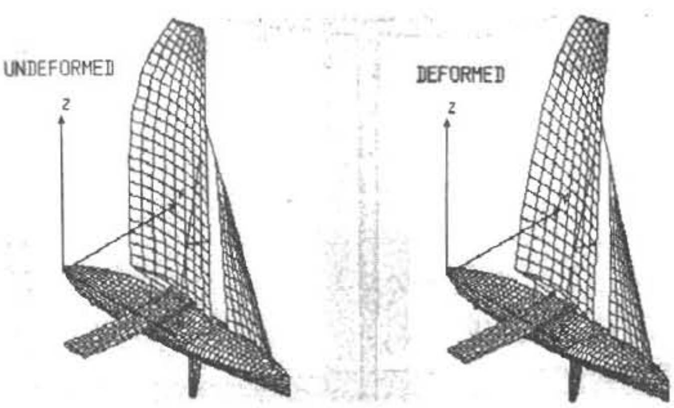

Fig. 8 Typical undeformed and deformed views

The results show that the carbon/epoxy boat had the largest bending stiffness due to its superior material properties. The different laminates used between the fiberglass and carbon boats illustrates the impact of double bias plies to reduce resin shear loading and increase fatigue life. For the same laminate the carbon and fiberglass boats deflected in equal ratios to their respective EA. The carbon/epoxy modulus is roughly three times that of unidirectional fiberglass. For this study the overall deflection criteria indicated that the carbon/epoxy boat with the mixed biaxial and double-bias laminate was 25.3% stiffer in the bow section than the wood IC, and 47% stiffer than the fiberglass boat.

Midsection torsion

Midsection torsion was evaluated at the mast step, the daggerboard centerline/shroud attachment, and at the forward end of the seat carriage. Torsional stiffness is important to maintain rig tension and rig/daggerboard alignment. Sectional torsion was calculated by taking two sets of opposing nodes at each section, and using their original and deflected positions to define the rotation. The results from these calculations are given in Table 7, and a typical rotated section is shown in Fig. 10.

Table 6 Bending deflections for baseline models

Model	∂ Bow, in.	∂ Shroud, in.	∂ Mast Step, in.	Total ∂, in.
Wood	0.1199	0.0982	0.0332	0.0684
Fiberglass	0.1785	0.1362	0.0463	0.0965
Carbon/epoxy	0.0922	0.0622	0.0158	0.0511

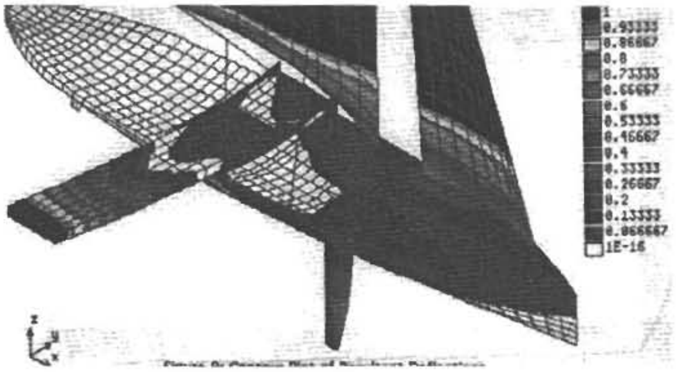

Fig. 9 Contour plot of resultant deflections

Table 7 Hull torsional rotation at three sections

Model	Rotation at Mast Step, deg	Rotation at Daggerboard, deg	Rotation at Forward End of Seat Carriage, deg
Wood	0.261	0.423	0.441
Fiberglass	0.415	0.640	0.694
Carbon/epoxy	0.221	0.311	0.374

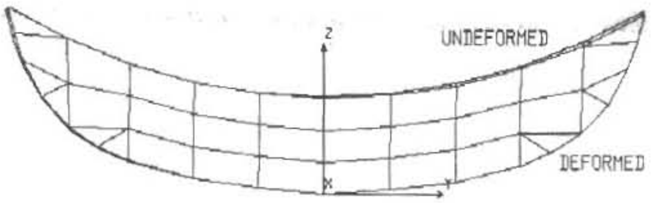

Fig. 10 Typical rotated section

As with bending stiffness, the carbon boat is stiffer torsionally. Here, the carbon/epoxy IC is an average of 19% stiffer torsionally than the wood IC, and an average of 48% stiffer torsionally than the fiberglass IC, much of which is due to the off-axis plies.

Pitch gyradius

Pitch gyradius was calculated by the FEA program, and is presented in Table 8. All three models were adjusted with "corrector weights" so that the total weight of the boat would be the same. This method approximates the class rules. Therefore, since the rig weights were also identical, a lower calculated pitch gyradius indicates a boat with a better distribution of weight fore and aft. This is important to the sailor because a lower pitch gyradius will provide better seakeeping for the boat, and is thought to improve performance.

The carbon/epoxy IC has the lowest pitch gyradius of the three models, although the differences are not great. The carbon/epoxy IC model's gyradius was 1.5% lower than the wooden boat FEA model's, and 1.8% less than that of the fiberglass boat FEA model.

Factors of safety

The factors of safety in the structures were determined using the Tsai-Wu failure criterion for laminated plates. This quadratic failure criterion produces an elliptical failure space which is more appropriate for laminated structures, where resin failure is important, than a maximum stress or strain criterion that includes shear effects.

The Tsai-Wu failure space equation is:

Table 8 Pitch gyradius for FEA models

Model	Pitch Gyradius, in.
Wood	40.598
Fiberglass	40.727
Carbon/epoxy	39.977

$$(1/X_t + 1/X_c) \times \sigma_1 + (1/Y_t + 1/Y_c) \times \sigma_2 - \sigma_1^2/(X_t \times X_c) - \sigma_2^2/(Y_t \times Y_c) + \tau_{12}^2/S^2 + (2 \times F_{12}{}^* \times \sigma_1 \times \sigma_2)/(X_t \times X_c \times Y_t \times Y_c)$$

where

X_t, X_c, Y_t, Y_c, S = material strengths
$\sigma_1, \sigma_2, \tau_{12}$ = material stresses
$F_{12}{}^*$ = Tsai-Wu interaction term

If the value of the equation is less than one, the structure has not failed, but if it is one or higher, failure has occurred. This formula can be used to find the factor of safety. One problem with the Tsai-Wu failure criterion is that no information is provided about the failure mode. Many engineers now use Hashin's failure criterion, which does provide information about the predicted mode of failure, but this option was not available in COSMOS/M. No information was available to verify the accuracy of the Tsai-Wu criterion for laminated wood structures.

The factors of safety for each model were found at the mast step, daggerboard case and the kingplank at the forestay connection. The results from these analyses are given in Table 9.

The carbon/epoxy boat showed the highest factors of safety in these three key areas. It is interesting to note that empirical construction development resulted in appropriate factors of safety in the strength-driven daggerboard case design. Figure 11 shows a contour plot of the stresses in the laminate material direction in the midsection of a typical IC model.

Conclusions and future developments

The finite element analyses indicated that carbon/epoxy can improve the bending and torsional stiffness, reduce pitch gyradius, and improve factors of safety. Although the fiberglass model did not perform as well as the all-carbon IC, using FEA to optimize the fiberglass laminates through changes in ply orientation, stacking sequence, hybridization, or fiber format (unidirectionals, woven roving, etc.) could result in a better-performing fiberglass IC for lower construction cost than the all-carbon cloth IC. Similarly, optimization of a wood canoe could also produce more competitive boats due to the inherently lower pitch gyradius than the fiberglass boats.

The current state of the art in sailing canoes, as well as other small sailing craft, is a result of many years of empirical development. Unlike the America's Cup where large research programs are commonplace, research and develop-

Table 9 Predicted factors of safety

Model	FOS in Mast Step	FOS in Daggerboard Case	FOS in Kingplank at Forestay
Wood	8.1	2.1	6.8
Fiberglass	3.7	1.7	7.0
Carbon/epoxy	9.1	2.6	8.3

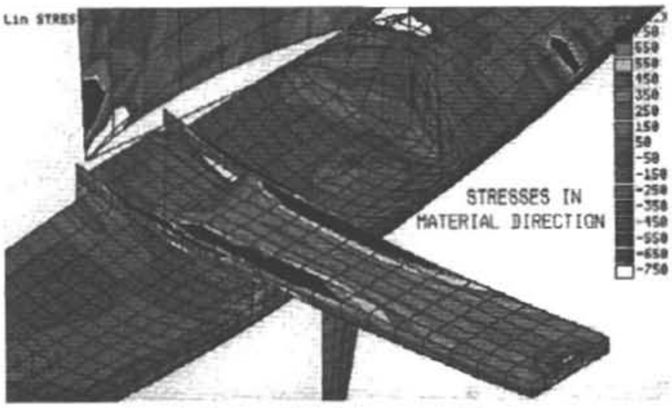

Fig. 11 Contour plot of stresses at midsection

ment in small craft is generally carried out at the expense of the small boat owner, and tested in developmental craft like the IC. With the development of inexpensive analysis tools like those used in this paper, greater analytical study will be available to guide small craft builders, owners and sailors to develop better performing, longer lived, and less expensive craft than those developed empirically.

In the International Canoe, room for improvement still exists in rigs, sails, foils, and hull construction. Experiments with rotating rigs, lighter rig construction, and tougher hulls will continue, and may find their way into mainstream sailing as full-batten sails and carbon masts have already. Many other small boat classes will continue to take advantage of the lessons learned in the development classes to improve their performance, increase the enjoyment of their sailors, or lower their costs through careful engineering.

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